

# Faint young Sun paradox remains

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## Brief Communication Arising

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The Sun was fainter when the Earth was young, but the climate was generally at least as warm as today; this is known as the ‘faint young Sun paradox’. Rosing et al. [1] claim that the paradox can be resolved by making the early Earth’s clouds and surface less reflective. We show that, even with the strongest plausible assumptions, reducing cloud and surface albedos falls short by a factor of two of resolving the paradox. A temperate Archean climate cannot be reconciled with the low level of CO<sub>2</sub> suggested by Rosing et al. [1]; a stronger greenhouse effect is needed.

During the Archean eon, the Earth received 76% to 83% of the energy from the Sun that it does today. If the Earth’s greenhouse effect and albedo were the same as

now, the Earth would have been in continual deep freeze until one billion years ago, with glaciers reaching the Equator. However, Archean glacial sediments are rare and geological evidence indicates that the Archean was typically warmer than today (we are in a glacial period now). With the amount of energy reaching the Earth given by  $F = \frac{1}{4}(1 - \alpha) = 239 \text{ Wm}^2$  (using the present-day solar constant  $S = 1368 \text{ Wm}^2$  and albedo  $\alpha = 0.3$ ), the radiative deficit in the Archean would have been  $(1 - 0.79)F < 50 \text{ Wm}^2$ . Resolution of the ‘faint young Sun paradox’ requires a positive radiative forcing—from reducing the albedo or increasing the greenhouse effect—of more than  $50 \text{ Wm}^2$ .

Clouds have two competing radiative effects: they reflect sunlight but they also add to the greenhouse effect if they are colder than the surface. Reflection dominates in low clouds, and the greenhouse effect dominates in high clouds. Therefore the absolute upper bound on warming by decreasing cloud reflectivity would be found by removing low clouds entirely. This gives a forcing of  $25 \text{ Wm}^2$ , half of what is needed to resolve the ‘faint young Sun paradox’ (our cloud model is described in the Methods). Any reduction to high clouds would cause a cooling.

Rosing et al. [1] justify less-reflective

clouds with the incorrect statements that most cloud condensation nuclei (CCN) are from biogenic dimethyl sulphide (DMS), and that DMS is solely produced by eukaryotes. DMS is also produced microbially [2]. Products of DMS contribute only 3% of Northern Hemisphere CCN and 10% of Southern Hemisphere CCN today [3]. Other biological [4] and non-biological sources, especially sea salt, provide CCN. If CCN production were to depend only on eukaryotic DMS emissions<sup>1</sup>, we would expect to see significant cooling when eukaryotes evolved, but no such cooling is evident.

Nevertheless, we can assume no biological CCN supply and quantify the resulting forcing. Over the modern ocean the effective radius  $r_e$  of cloud drops rarely exceeds  $15\text{ }\mu\text{m}$  [5] even in remote and unproductive regions (the  $r_e$  of  $17\text{ }\mu\text{m}$  to  $30\text{ }\mu\text{m}$  used by Rosing et al. [1] is too high). For an upper bound, we increase low cloud droplet size by 50% from our standard case, from  $11\text{ }\mu\text{m}$  to  $16.5\text{ }\mu\text{m}$ . With no change in cloud thickness, the forcing is  $7\text{ Wm}^2$ . Clouds with larger drops may rain out faster. Parameterizations of enhanced rain-out vary from proportional to  $(r_{e,0}/r_e)^1$  to proportional to  $(r_{e,0}/r_e)^5$ .<sup>37</sup> [6,7]; the corresponding extra forcing would be  $4\text{--}15\text{ Wm}^2$  (remote sensing data for marine stratus suggest that the low end of this range is more appropriate [8]). The sum is  $11\text{ Wm}^2$  to  $22\text{ Wm}^2$ , with the low end being most likely.

The authoritative estimate of the global energy budget [9] gives global mean and ocean albedos of 0.125 and 0.090 respectively. The largest realistic surface darkening is from the present mean to an all-ocean world, which gives a radiative forcing of  $5\text{ Wm}^2$ .

Increasing the  $\text{CO}_2$  mixing ratio to 1000 parts per million by volume (p.p.m.v.; the upper bound according to Rosing et al. [1]) gives a forcing of  $6\text{ Wm}^2$ . Rosing et al. [1] rely on 1000 p.p.m.v.  $\text{CH}_4$  for much of their warming, ignoring relevant atmospheric chemistry. As the partial pressure of  $\text{CH}_4$  ( $p\text{CH}_4$ ) approaches that of  $\text{CO}_2$  ( $p\text{CO}_2$ ), hydrocarbon haze forms in the stratosphere, the cooling effect of which outweighs the greenhouse effect of  $\text{CO}_2$  and  $\text{CH}_4$  [10,11]. Numerical models [12] predict haze production when  $p\text{CH}_4 / p\text{CO}_2 \geq 50.1$  and haze production has been seen in laboratory experiments<sup>13</sup> where  $p\text{CH}_4/p\text{CO}_2 = 0.3$ . With 1000 p.p.m.v.  $\text{CO}_2$ , the maximum  $\text{CH}_4$  concentration that can give warming is 300 p.p.m.v., which would contribute  $7\text{ Wm}^2$  of additional forcing.

Changes to clouds could in theory considerably reduce the amount of greenhouse gases required, because gaseous absorption depends on the logarithm of gas abundance. But even with the highly unlikely assumption of no biological CCN supply, cloud changes can provide only one-quarter to one-half of the required radiative forcing. Any changes to clouds would require strong justification, which Rosing et al. [1] do not provide. A strong greenhouse effect is required in the Archean. The alternative is an extremely cold climate with continual mid-to low-latitude glaciation, for which there is no evidence

**Methods** We calculate the radiative forcing (change in net flux at the tropopause) on a single global annual mean atmospheric profile, with three layers of clouds that overlap randomly [14]. The radiative fluxes on eight sub-columns corresponding to each cloud combination are cal-

culated with the RRTM model [15]. For our standard case, cloud water paths are  $[W_{\text{high}}, W_{\text{mid}}, W_{\text{low}}] = [20, 25, 40] \text{ gm}^2$ , fractions are  $[f_{\text{high}}, f_{\text{mid}}, f_{\text{low}}] = [0.25, 0.25, 0.40]$  and the surface albedo is 0.125. Standard low and mid-level clouds are liquid with  $r_e = 11 \mu\text{m}$  and high clouds are ice with generalized effective size of  $D_{ge} = 75 \mu\text{m}$ . For radiative forcings described in the text, the low cloud water path is varied but all other parameters are unchanged.

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